A Giant Leap for Space Telescopes

Eyeglass is a lightweight, flexible, and foldable space optic.

BREATHTAKING images from the Hubble Space Telescope, with its 2.5-meter mirror lens, have delighted astronomers and the public for years. Now, the National Aeronautics and Space Administration (NASA) has announced plans for a progression of larger telescopes to be fielded in space over the next two decades. These include telescopes with primary optics whose apertures are 25 meters and more. The increased sensitivity and resolution of the giant space telescopes will allow astronomers to view extremely fine features on planets and their moons in our solar system, image the cores of distant galaxies, and probe the edges of the universe.

"The history of astronomy is dominated by the quest for larger and higher quality telescopes," says Livermore physicist Rod Hyde. He notes, however, that using a giant optic in space raises this quandary: how to design large-aperture space optics that are both optically precise and can meet the size and weight requirements practical for launch and deployment. "Either of these challenges is, by itself, quite formidable; in concert, they have yet to be solved," he says.

Hyde heads a Livermore team that has developed a radically new concept to overcome the difficulties inherent in building and fielding a high-quality space telescope far larger than ever deployed. The concept, called Eyeglass, uses diffractive optics (also called Fresnel lenses) instead of mirrors or conventional glass lenses.

A Fresnel lens is flat on one side and ridged on the other. It replaces the curved surface of a conventional lens with many concentric grooves that are etched into a thin sheet of glass, silica, or plastic to bend and focus light. Relatively crude Fresnel lenses are commonly found in traffic signal lights, vehicle headlights, and the rear windows of motor homes.

Neatly Packaged, Easily Fielded

Not only is the Eyeglass diffractive telescope lightweight, but it also is flexible and can be segmented and folded into a neat package that fits in a space launch vehicle, says Hyde. Eyeglass would be easy to field in space because as a thin, flat membrane, it would not need large, heavy backings, trusses, or motors to maintain its shape, as do telescopes using mirrors.

"Conventional glass lenses and mirrors are far too thick and heavy for large-aperture space optics," Hyde says. "Diffractive optics would make an ideal lens in space; they would revolutionize deep-space astronomy."

Hyde conceived the approach of using diffractive lenses for large-aperture space optics in 1996. Since then, the concept has been studied under Laboratory Directed Research and Development funding and, more recently, with support from federal agencies. About eight researchers were assigned to the project from Livermore's National Ignition Facility (NIF), Chemistry and Materials Science, Engineering, and Physics and Advanced Technologies directorates.

The project takes advantage of long-standing Livermore experience in manufacturing diffractive glass optics for high-power laser systems such as the Petawatt (see *S&TR*, March 2000, pp. 4–12) and NIF, currently under construction at Livermore. NIF will use nearly 1,000 diffractive optics components, mostly of 40-centimeter-diameter size. A significant number of the components are being manufactured at Livermore, which has the only facility in the world that can make precision diffractive optics of more than a few centimeters in diameter.

Diffractive optics can be made so that they either reflect light (like a mirror) or transmit it. Mirrors pose serious disadvantages because they are extraordinarily sensitive to the slightest bump or ripple on their polished surfaces. A diffractive optic that transmits light, however, is not severely distorted by surface ripples produced during its operation. Light passing through a surface ripple experiences the same optical path as light passing next to the ripple, thereby virtually eliminating distortion. And by making the diffractive optic slow—that is, by focusing the incident light farther away from the optic—its surface ripple tolerance can be made up to 100,000 times greater than for mirrors.

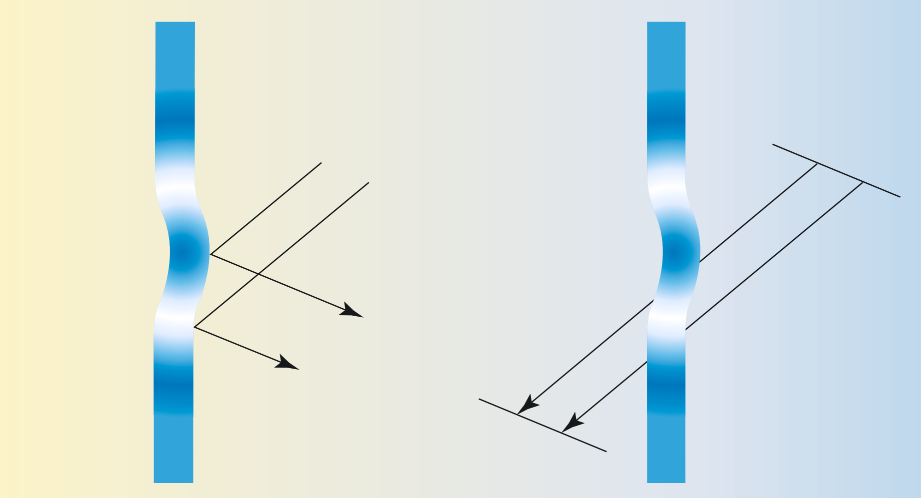
No Motors Required

Mirrors also commonly require a stiff external skeleton or small motors to maintain their precise shape to within a few tenths of a nanometer. Such ancillary systems, which increase weight and complexity, are unnecessary in transmissive diffractive optics.

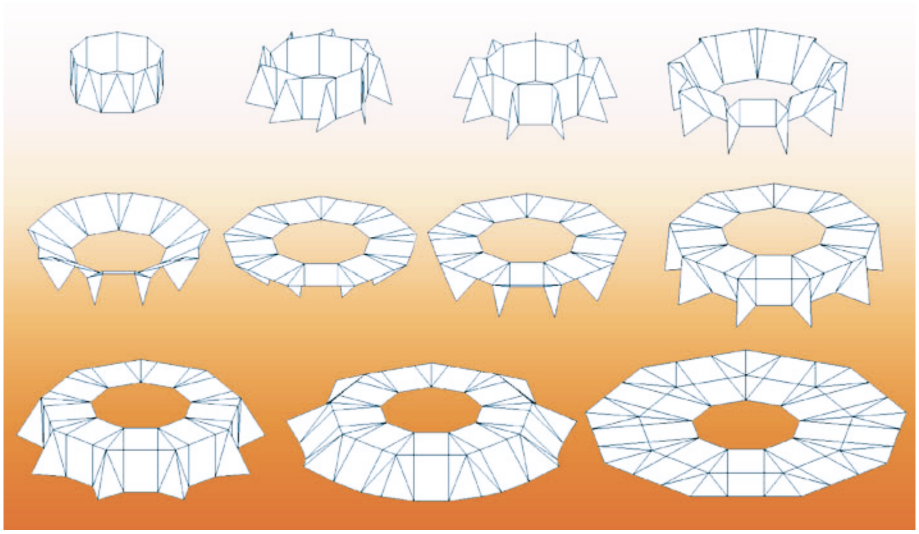
Furthermore, transmissive diffractive lenses are themselves more lightweight. Compared to traditional lenses, the amount of optical material that is required to focus light with a diffractive lens is quite small. For example, Hubble's 2.5-meter mirror weighs 800 kilograms. A 25-meter mirror made more lightweight by removing all unnecessary bulk would still weigh 7,000 kilograms, far too bulky and heavy to be launched. Likewise, a 25-meter traditional glass lens would probably measure 6 centimeters thick and weigh about 45,000 kilograms. In comparison, a 25-meter diffractive lens made of 10-micrometer-thick plastic would weigh only 10 kilograms.

One of the challenges of fielding a large space telescope is finding a method for stowing it in a space launch vehicle whose diameter is smaller than the lens's. The Livermore team has found in origami, the ancient Japanese art of paper folding, a promising approach to temporarily contract a lens made of many repeating segments. The principles of origami are commonly used for map folding as well as product packaging. The team has worked with origami expert Robert Lang to identify and then simulate several folding patterns for lenses of various sizes, including a 5-meter lens. The sequences necessary to compactly fold lenses of many segments have proved workable in prototypes using plastic and glass panels.

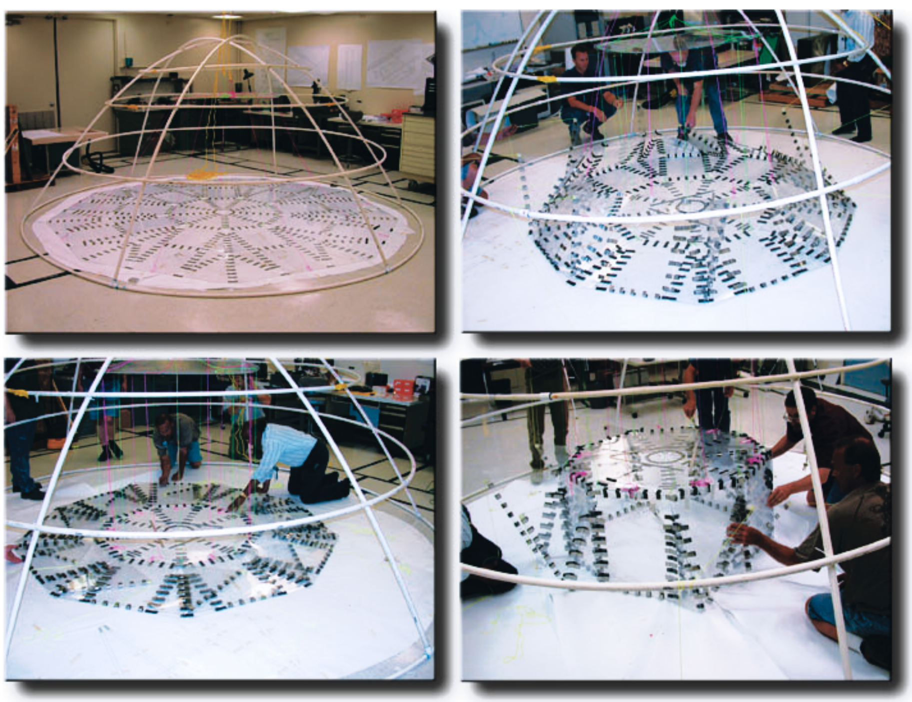
"It's difficult to fold something that is curved, like a mirror. It's much easier to fold something that is flat, like a diffractive lens, especially one that is made of many flat segments," says Hyde. He cites concerns about whether a lens made of many fragile glass segments can survive the severe



In contrast to common mirror lenses, transmissive diffractive optics are relatively insensitive to surface imperfections such as bumps and ripples. Because mirrors reflect light, surface ripples double the magnitude of the bump. Light passing through a ripple on the surface of a thin glass or plastic diffractive optic experiences the same path as light passing next to the ripple, thereby minimizing any distortion.



The Livermore team found in origami, the ancient Japanese art of paper folding, a practical way to fold and store a lens made of many segments. The team identified and then simulated several folding patterns for lenses of various sizes.



Early in 2002, the team, guided by computer simulations, assembled a two-thirds scale model of a 5-meter lens using unpolished and unetched plastic panels and successfully demonstrated the origami-like folding pattern. The folding process used strings attached from an overhead structure and secured to individual panels. Four of the steps of the folding process are depicted here. The final step (not shown) was folding the lens into a configuration measuring 1.2 meters in diameter and about 55 centimeters high.

vibrations that are associated with launch. The best approach appears to be to separate the panels with soft, disposable packing material so that the panels don't touch one another and then to pack the assemblage tightly.

A Color-Corrected Telescope

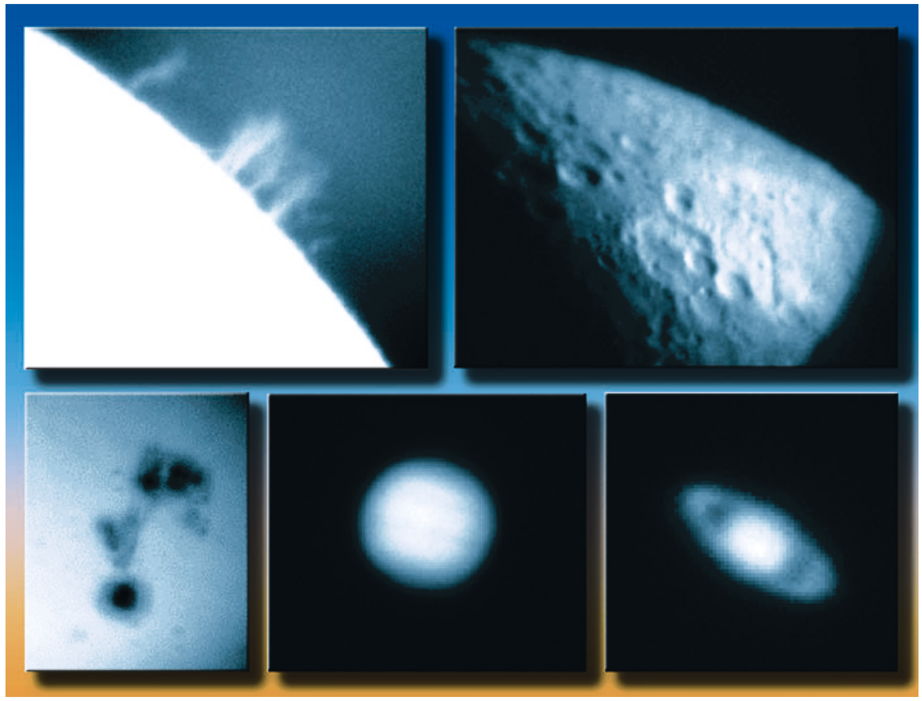
The team has been building and testing increasingly advanced diffractive lenses with materials that are considered suitable for space missions. They started by defining the requirements for a space mission, selecting and characterizing the best materials to make a diffractive lens, and developing fabrication technologies. Then they built a series of progressively larger diffractive telescopes and demonstrated a way to correct for chromatic (color) aberrations.

One of the great challenges of making diffractive lenses suitable for astronomical imaging, says Hyde, is that a diffractive Fresnel lens focuses different wavelengths of light at different points in space, thereby distorting the color characteristics of the image. Because of this effect, diffractive lenses are mostly used for applications needing only one wavelength—a monochromatic application—such as for lasers. In principle, chromatic aberrations can be eliminated by using a relay lens to reimage an object from the first diffractive lens onto a second diffractive lens, or inverse Fresnel lens, which then corrects the aberrations.

In 1999, the team developed a color-corrective optic and incorporated it into the first large-aperture diffractive telescope. The primary Fresnel lens was 20 centimeters in diameter and had a focal length of 20 meters. The lens was fabricated by a photolithographic process that etched a series of diffractive grooves into 10-millimeter-thick glass. The chromatic correction system included a 4-centimeter relay lens and a 2.2-centimeter inverse diffractive lens. The team demonstrated the color correction function of the system by bringing broadband light (from 470 to 700 nanometers) to a common focus. Without the correction system, numerous focal spots generated by the primary lens would span a 7-meter distance.

The team then used the telescope to obtain full-color images of the lunar surface, solar flares, Jupiter, and Saturn. “This telescope successfully demonstrated that diffractive lenses can be used for imaging over more than an extremely narrow bandwidth,” says Hyde.

Four years ago, Eyeglass received its first external funding, which was used to construct a 50-centimeter-diameter, color-corrected, f/100 (lens aperture setting) diffractive telescope. The relatively large diameter and slow f-number of this lens produced a 50-meter-long telescope. The team used the laser bay of the Laboratory’s now-disassembled Nova laser to provide a large, vibrationally and environmentally controlled beam path, which is needed for optically testing the telescope.



In 1999, the team developed a color-corrective optic and incorporated it into the first large diffractive telescope. This telescope, which measured 20 centimeters in diameter and 20 meters long, successfully imaged the lunar surface, sunspots, solar flares, Jupiter, and Saturn.

First Segmented Lens

Satisfied that they could manufacture diffractive telescopes capable of operating over all the wavelengths of visible light, the team began work on overcoming the packaging challenge for deploying a diffractive lens in space. Livermore physicist Sham Dixit, who oversaw fabrication and assembly of the Eyeglass lenses, notes that fabricating a single precision diffractive optic of 5 meters, let alone one measuring 25 meters, is far beyond current capabilities. However, even if the team could manufacture a 25-meter piece of glass, it could never be stowed in a spacecraft and launched into space. As a result, the Livermore team focused its efforts on designs that stitch many individual pieces into one large lens.

Dixit says the multipanel approach is attractive because it splits the fabrication task into two efforts: optical engineering for creating many meter-scale lens panels and mechanical engineering for precisely aligning and joining the panels. The use of multiple panels also provides a practical way to fold the lens because all folding occurs at metal joints connecting the flat panels. “The joint has to fold, but the panels do not,” says Dixit.

In 2001, in an attempt to demonstrate the feasibility of the multipanel approach, the team built its first segmented lens. The lens measured 75 centimeters in diameter and was assembled from six panels precisely aligned and joined to each other. In optical tests, the lens produced a tightly focused spot. Following this demonstration, the team folded the lens into the shape of a piece of pie, unfolded it into a flat lens again, and observed that the focal spot did not degrade from the folding–unfolding operation. “We achieved our goal of demonstrating that high-quality, thin, segmented diffractive lenses could be built with sufficient alignment and seaming accuracy,” says Dixit.

Hyde acknowledges some disadvantages to making a large lens from smaller pieces. The 2- to 4-centimeter gaps between the segments scatter a small amount of light that could obscure tiny details, for example, during an attempt to detect a planet rotating around a much brighter star. Also, the metal seams holding the panels together expand at a different rate than glass, thereby causing a small amount of distortion at the panels' edges. Nevertheless, Hyde says, the advantages of a design of multiple segments far outweigh the disadvantages.

Last year, the team began work to produce 72 glass panels and precisely assemble them into a 4.7-meter diffractive lens that could be compactly packaged and deployed in space to meet the space and weight requirements of NASA and other federal agencies. "Our objective was to fabricate a diffractive lens that is lightweight, foldable, of high resolution, and that can be scaled up for larger space-based lenses," says Dixit.

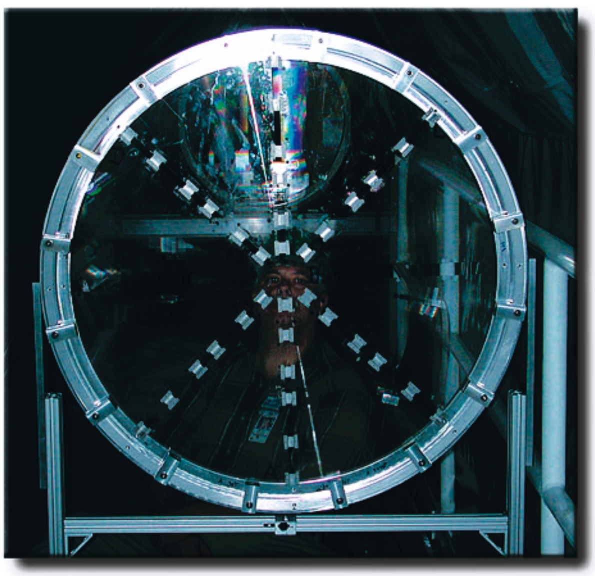
Panels Polished and Etched

To make the individual lens panels, the team started with sheets of commercial zinc borosilicate glass measuring 1,150 by 850 by 0.7 millimeters. This type of glass was selected because it is not expensive and is widely used in laptop computer displays and microscope slides. Forty 700- by 800-millimeter panels were required for fabricating the 72 panels.

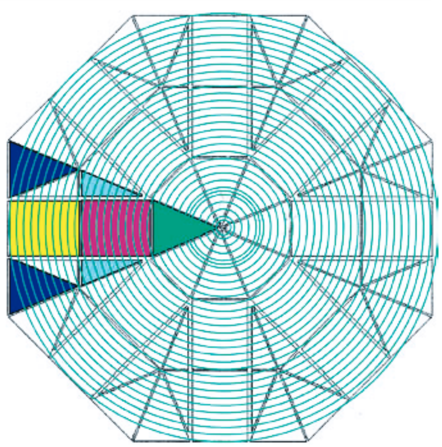
The glass sheets contained several micrometer-deep ripples; they needed to be smoothed to a flatness within about 0.1 micrometer to obtain the required optical quality. Because traditional grind-and-polish techniques are expensive and become increasingly risky for thinner and thinner sheets of glass, the team explored other methods. The most promising approach was a wet-etching method developed by Livermore scientists Jerry Britten and Mike Rushford. They polished thin glass sheets using a controlled application of acid etchant. This technique polishes the glass without stressing it. In 2001, the team demonstrated the effectiveness of this process and built a machine for smoothing glass sheets.

The thin glass sheets were inscribed with a precise pattern of 0.5-micrometer-deep grooves. To inscribe the grooves, the team used photolithographic surface-patterning methods similar to those used in the semiconductor industry. A coating technique, developed at Livermore, laid down a precise thickness of liquid photoresist on the lens surface, and an optical pattern was illuminated through a mask onto the photoresist.

All told, the 72 panels contain 19,105 circular grooves. The grooves, about 0.5 micrometer deep, range from 60 micrometers to several millimeters wide. The grooves are arrayed concentrically, starting from the centermost panels and continuing to the perimeter of the outermost panels. The concentration of grooves ranges from about 1 line per centimeter at the very center of the assembled lens to about 16 lines per millimeter at the outer edge.



In 2001, the team built its first segmented lens. The lens measured 75 centimeters in diameter and was assembled from six foldable panels precisely aligned and joined to each other.



The final 5-meter lens is composed of 72 segments: 16 rectangles measuring 654 by 790 millimeters, 32 right triangles measuring 327 by 790 millimeters, and 24 isosceles triangles measuring 654 by 790 millimeters. The panels are divided into eight "petals" consisting of three isoceles triangles, four right triangles, and two rectangles. Each petal covers 45 degrees, or one-eighth of 360 degrees. One of the petals is highlighted. The circular lines suggest some of the 19,105 circular etched grooves that focus the light.

Assembling the Panels

The 72 lens panels were cut into precise rectangular and triangular shapes for assembly into the complete lens. The assembly, done by a group led by engineer Andrew Weisberg, used the same process demonstrated on the 75-centimeter lens but upgraded to account for the larger size, panel count, and tolerance requirements of the 5-meter lens. Dixit notes that when working on individual panels, one must never lift them by the edges but rather slide them on a smooth backing, much like using a pizza paddle.

Once a panel was in the proper location, it was joined to its neighbors by gluing each piece to foldable metal. Having panels out of register, says Dixit, would be disastrous to image quality. Precision alignment can be ensured by matching fiducials (tiny marks) etched along the common borders of neighboring panels to a precision of 1 to 2 micrometers. About 250 micrometers thick, the seams can withstand forces much greater than those it would likely experience during deployment in space.

The assembled 5-meter lens has a focal length of 250 meters and an optical speed of f/50. Its 72 panels include 16 rectangles measuring 654 by 790 millimeters, 32 right triangles measuring 327 by 790 millimeters, and 24 isosceles triangles measuring 654 by 790 millimeters. The panels form eight "petals," each consisting of three isoceles triangles, four right triangles, and two rectangles. Each petal covers 45 degrees, or one-eighth of 360 degrees.

With this configuration of repeating triangles and rectangles, the entire lens can be folded in an intricate but foolproof manner and fit into a hatbox measuring 1.75 meters in diameter and about 80 centimeters high. The team gained confidence in the folding patterns by building subscale models from plastic and glass panels.

Following assembly, the lens was mounted in a steel frame and a mesh of aluminum bars on each side to keep the lens rigid for transportation to an outside testing location and to protect it against winds. Although the team verified the characteristics of the individual panels during the fabrication and assembly process, optically testing the complete lens was still required.

Upon delivery at its testing location, the horizontal lens was lifted by a crane to a vertical position and then secured. The lens was illuminated at night with 532-nanometer laser light, producing 1- to 2-centimeter-diameter image spots. Although the optical test was successful, Hyde calls it a rudimentary test because, as expected, air currents and the lack of the panels' complete flatness caused some distortion of the focused spot. An ideal testing environment, Hyde says, would be an underground tunnel at the Department of Energy's Nevada Test Site. Nevertheless, the test at Livermore was considered appropriate for this first-generation lens.

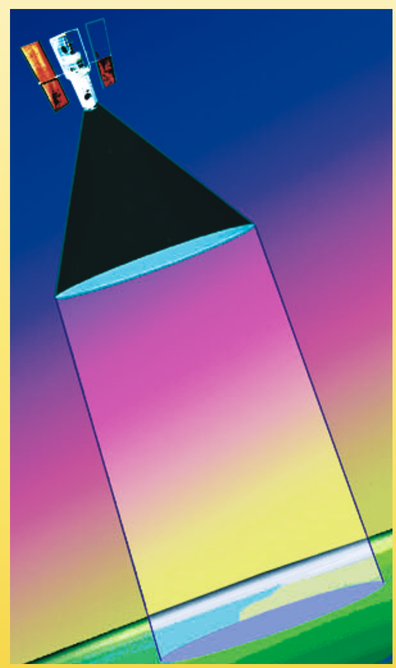
Magnifying Glass and Eyepiece at Work in Space

In high Earth orbit, the Livermore-conceived Eyeglass diffractive telescope would consist of two spacecraft: a 25-meter-aperture Magnifying Glass and a 1-meter-aperture Eyepiece. Two vehicles are required because of the Eyeglass telescope's large aperture and optical slowness. That aperture and optical combination confers large manufacturing tolerances but also dictates a focal length of about 1 kilometer. Such a length is impractical for a single spacecraft, so the Eyeglass telescope would be split into two separate but cooperating vehicles.

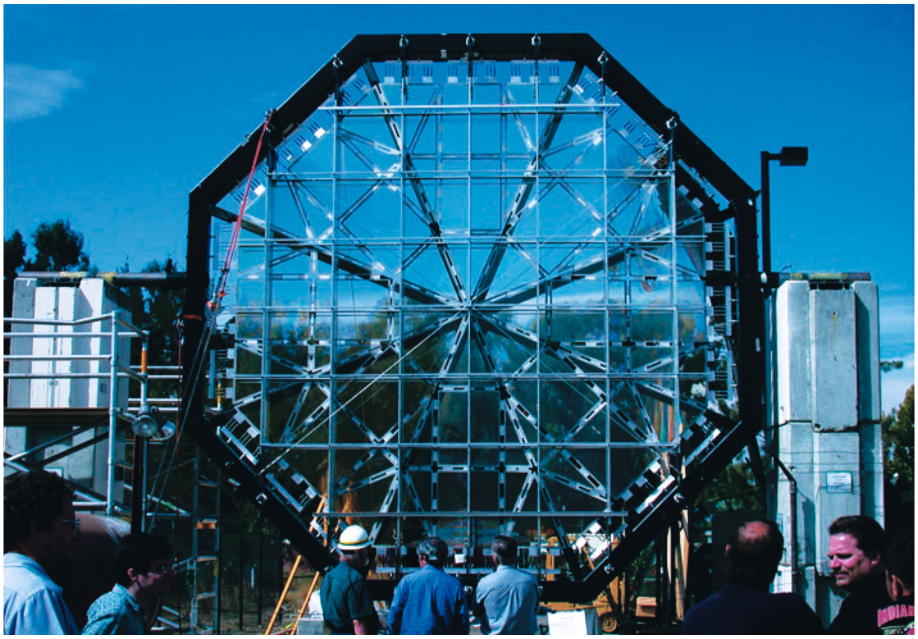
Under this arrangement, the Magnifying Glass vehicle holds the large-aperture diffractive lens and, with the aid of a gyrowheel, swivels the lens to point toward desired targets. The Magnifying Glass gathers and focuses light to a spot about 1 kilometer away, where the light is collected by the mobile Eyepiece. The compact Eyepiece also performs the color correction necessary to obtain accurate images in visible light of all wavelengths. "The two separate vehicles must remain properly aligned so that they function together as a high-precision, steerable telescope," says Livermore physicist Rod Hyde, creator of the Eyeglass concept.

Hyde says that after being deployed in space, the giant lens would be kept flat by being held in tension by rotating the lens along its axis at about 10 revolutions per minute. However, spinning would make it harder to swivel the Magnifying Glass so it could image another target. Hyde solves this problem by placing a counter-rotating gyrowheel inside the center of the lens. Although the gyrowheel would replace the centermost glass panels, these make up only a small portion of the lens and are not essential.

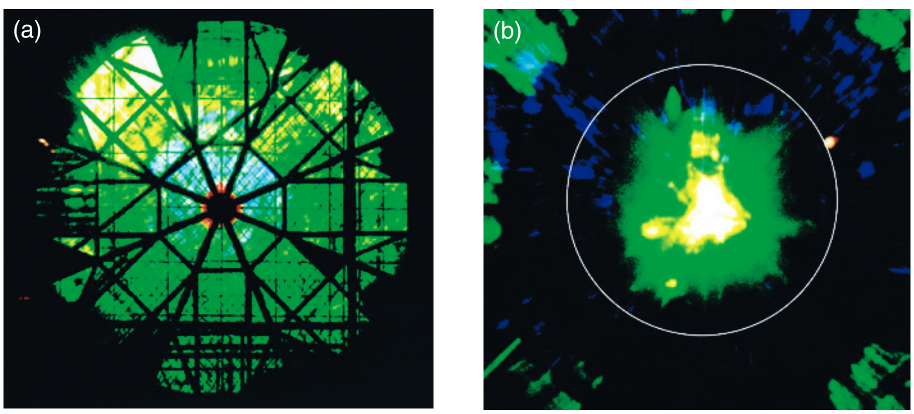
While in space, the thin glass panels must withstand exposure to meteoroids and vacuum, sunlight, and radiation. Fortunately, glass holds up well to the extreme conditions of space. Hyde calculates that based on data recorded by existing satellites, a 10-year exposure in space would result in damaging one ten-thousandth of the Eyeglass lens surface. Impact from meteoroids would likely create either craters or holes located about every 2.5 centimeters and many accompanying cracks. Fortunately, the cracks would not grow because the lens would be under low tension. Also, the lack of water vapor in space makes glass much more resistant to spreading cracks.



The Eyeglass diffractive telescope would consist of two spacecraft: a 25-meter-aperture Magnifying Glass and a 1-meter-aperture Eyepiece.



The completed lens, mounted in a steel and aluminum frame and ready for optical testing.



(a) The lens during optical testing. Some of the panels are obstructed by the supporting frame. (b) The 1- to 2-centimeter focal spot produced by the lens when illuminated with 532-nanometer laser light.

On the Map

The lens is, by a wide margin, the largest optical-quality lens in the world. For example, it has twice the diameter of the primary mirror for the Hubble Space Telescope, yet is 10 times lighter.

"A 5-meter lens is a big-league optic. Demonstrating such a large Fresnel lens places diffractive optics firmly on everyone's map," says Hyde. "By making the lens from technology that is scalable to much larger sizes and from space-deployable materials, we have demonstrated the technology and the here-and-now reality of diffractive telescopes."

A 5-meter diffractive space telescope could be deployed in space within two to three years, says Hyde. A 25-meter or larger version could be deployed within a decade.

The team is exploring preliminary partnerships with U.S. agencies that could benefit from diffractive telescopes. Discussions have focused on design, technology development, and demonstrations of lenses of 5 meters and larger. Hyde also plans to establish partnerships with traditional space contractors. The Livermore role in these partnerships would be to support the optical and deployment designs and serve as the fabrication house for the lenses.

One option under exploration is obtaining even thinner glass sheets to save additional weight. Another option is fashioning a lens from segments made of polymer films. A plastic lens would be less prone to damage from launch vibration, would weigh less, and could be fashioned from multiple panels that are larger than their glass counterparts. The Livermore team has carried out research on polymer films and done etching on several meter-size panels.

Hyde adds that the technology developed at Livermore could be used for more than astronomy. Lightweight diffractive optics of greater than 10 meters would likely be used in applications such as Earth observation and optical communications. Closer to home, "Everything we're learning about making diffractive optics benefits the National Ignition Facility and high-powered lasers everywhere," he says.

The Livermore team has put diffractive telescopes on the map. The next job is putting them into space.

—Arnie Heller

Key Words: diffractive telescope, Eyeglass, Eyepiece, Fresnel lens, Hubble Space Telescope, Magnifying Glass, National Ignition Facility, photolithography.

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For more information about diffractive optics:

www.llnl.gov/nif/lst/diffractive-optics/newtecheye.htm